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Anchor safety potential reinforcing theory and its applications in roadway affected by mining

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Abstract

The roof collapse accident happens frequently in the mining affected roadway reinforced by anchors, which makes the roadway unsafe. Based on the damage analysis of roof strata, composite material mechanic rationale is adopted to deduce the calculating formulas of anchor reinforcing potential coefficient which is represented by the ratio of the limit roof collapse span between after anchor reinforcement and before anchor reinforcement. By using anchor reinforcing potential coefficient, this paper puts forward a new anchor support calculating method for the roadway affected by mining. It has been tested in Yanzhou mining area and Xinwen mining area. The results show that the new method is safe and reliable, and valuable for generalization

Keywords: anchor reinforcement; potential; roadway; mining

1. Introduction

From the view of the safety and economical problems, the stability control of fractured surrounding rock roof is one of the principal problems for deep underground coal mining engineering. As the effective approaches for controlling large deformation and rock burst [1], the theory and technology of anchor reinforcement have been researched. For example, the use of roof bolt systems in high stress weak roof was successful [2]. In order to improve the bolt reinforcing quality, it was proposed that the anchor cable and bolt should have high strength, big extending capacity and high pre-pressing force in anchorage section [3]. By considering the bearing capacity of rocks, a reinforced active support was presented which is consisted of the cable-reinforced roadside supporting technique and the roadway bolt-supporting technique [4]. The investigations were made on the main factors including not only anchor length, bore-hole diameter, resin capsule packaging, water, etc.[5], but also the adverse geological conditions and geometry of opening [6]. Some studies [7-8] showed that the initial supporting stiffness and strength of bolting system should be increased largely in order to maintain the integrity, reduce the strength degradation and the dilitancy of surrounding rock.

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Besides laboratory experiments and in-situ monitoring techniques, analytic method and numerical simulations were also used. For example, a systemic analysis was made for the tie-rods and inclined roof bolts as well as three upper and lower bounds [9]. An analytical design method was advanced for the fractured rock roof reinforced by inclined roof bolts and a horizontal tie-rod [10]. By making use of the Boussinnesq solution in solid mechanics, the research was made on the calculating methods of stress and transverse compression force caused by a single pre-tensioned bolt in surrounding rock [11]. Timoshenko beam model was used to study the stability of surrounding rocks of a cut in soft and thick coal seam which is supported by the bolt-mesh-anchor technology and excavated by fully-mechanized sublevel caving system [12]. An idea of pretension bolt with high strength was also put forward by analyzing the weakness of the commonly-used bolt supporting [13]. Aiming at the characteristics of nonlinear mechanical process of surrounding rock in deep gateway excavation and support, the space-time action rule of bolt-net-anchor coupling support was researched by numerical simulation method [14-15].

In practice, in order to improve bolting effectiveness, the roof bolts with glove fingering of the resin cartridge and un-mixing of the resin mastic was tested [16] and a new structure of FRP bolt-end was used [17]. Furthermore, a series of laboratory based push and pull tests were carried out to investigate the influence of profile configuration on the load transfer mechanism of bolt/resin interface [18].

So far, the anchor reinforcing potential for different rock masses is still a very important problem need to research.

2. Analytical model for bolting potential

2.1. Roof damage model

As shown in Fig.1, assume that bending deformation appears when roof bears a uniform load. The roof is taken as a beam with unit width and 2h in height along cross section of roadway. Obviously, the upper part of roof is in the compressive state and the lower part of roof is in the tensile state. In the compressive zone $\sigma < 0$, $D = 0$ (D is the damage variable), the limit effective stress $\tilde{\sigma} = \sigma$. In the tensile zone $\sigma > 0$, $D > 0$, $\tilde{\sigma} = \sigma/(1 - D)$. This indicates the effective stress increases with the increasing damage in the tensile zone. According to the stress-strain relation $\tilde{\sigma} = E\varepsilon$, when the deformation obeys the plane cross-section assumption, $\tilde{\sigma}$ and ε are linear in destruction along roof height. The bearing capacity of tensile zone decreases and the neutral axis shifts to the compressive zone because of damage. If y_0 represents the position of neutral axis, the interior force in compressive zone is

$$N_C = \frac{1}{2} b(h + y_0)\tilde{\sigma}_1 = \frac{1}{2}(h + y_0)\tilde{\sigma}_1 \tag{1}$$

where $\tilde{\sigma}_1$ is the effective compressive stress, $\tilde{\sigma}_1 = \sigma_1 = E\varepsilon_1$.

If the damage modulus is represented by k and satisfies

$$D = \begin{cases} \tilde{\sigma}/k & \tilde{\sigma} > 0 \\ 0 & \tilde{\sigma} \le 0 \end{cases} \tag{2}$$

then in the damage zone, the tensile interior force N_t is

$$N_t = \int_{y_0}^{h} dN_t = \frac{1}{6}(h - y_0)(3 - \frac{2\tilde{\sigma}_2}{k})\tilde{\sigma}_2 \tag{3}$$

The acting position of N_t is

$$y_t = \frac{1}{2}\left(\frac{1}{3 - \frac{2\tilde{\sigma}_2}{k}}\right)\left[4h + 2y_0 - \frac{\tilde{\sigma}_2}{k}(3h + y_0)\right] \tag{4}$$

and y_0 is obtained based on the condition of equilibrium by

$$y_0 = -0.101h \tag{5}$$

If considering limit damage state, the uniaxial tensile strength is $\tilde{\sigma}_2 = k/2 = [\sigma_t]$. So the limit bending moment M_t is obtained by

$$M_t = 0.473[\sigma_t]h^2 \tag{6}$$

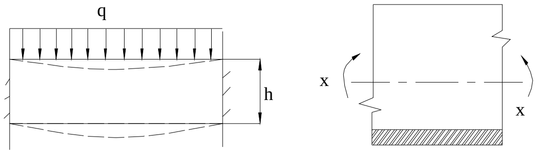

Fig. 1. Stress and strain of bending rock beam

2.2. Composite reinforcing mechanism

Compared with the steel bar, rock is a typical kind of brittle material with low tensile strength. When minor tensile strain ε_r occurs in rock, the tensile stress will arrive at limit elastic stress σ_r'. But anchor has not only a high tensile strength σ_b' but also large limit tensile strain ε_b. The tensile mechanical property of composite body of rock and anchor can be described by three stages, as shown in Fig.2

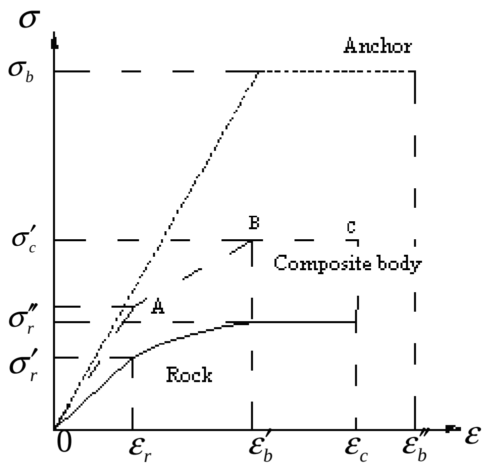

Fig. 2. Stress-strain curve of bolted rock

Stage OA : the tensile strain is in the range $0 \le \varepsilon < \varepsilon_r$, in which only elastic deformation occurs for both rock and anchor of the composite body, and Young's modulus is

$$E_c = (1-f)E_r + fE_b \tag{7}$$

where E_r and E_b are the Young's modulus of rock and bolt, f is the volumetric ratio of anchor to composite rock body.

Stage AB: By using Mohr-Coulomb criterion, the equivalent tensile strength of bolted rock is obtained by

$$\sigma_r'' = \frac{2c'\cos\varphi}{1+\sin\varphi} \tag{8}$$

where c' is the cohesion of composite rock body, φ is the interior friction angle.

When the tensile stress arrives at the limit tensile strength of anchor, the composite body will also arrive at its ultimate tensile strength, and meanwhile the strain is in the range $\varepsilon_r' \le \varepsilon < \varepsilon_b'$. The tensile strength of composite body can be estimated by

$$\sigma_t' = f\sigma_b + (1-f)\sigma_r'' \tag{9}$$

where σ' is tensile strength of composite body, σ_b and σ_r'' are the anchor tensile strength and rock tensile strength.

Stage BC: after the composite rock body arrives at its ultimate tensile strength, it keeps constant in the range. The composite body strength depends on rock mechanical properties of c and σ_c, as well as strength and amount of anchor.

2.3. Bolting potential

As shown in Fig.3, the limit collapsing span of a roadway roof can be estimated from formula (6), in terms of the brittle tensile damage analysis mentioned above.

$$l_1 = \sqrt{\frac{5.676[\sigma_t]}{q}h} \tag{10}$$

where h is the thickness of roof to be bolted, q is the distribution load on roof, l_1 is the limit collapsing span of roof without being bolted.

After the roof is reinforced by anchors, the strength of composite roof will be enhanced, and the limit collapsing span of roof will increase to l_2 which can be estimated by above composite analysis and is obtained by

$$l_2 = \sqrt{\frac{5.676[\sigma_t]_c}{q}h} \tag{11}$$

where $[\sigma_t]_c$ is the equivalent tensile strength of bolted roof, l_2 is the limit collapsing span of bolted roof.

From (8), (9) and (11), the limit collapsing span ratio of l_2 to l_1 is

$$\mathrm{K} = \frac{l_2}{l_1} = \left(\frac{f\sigma_b + (1-f)\dfrac{2c'\cos\varphi}{1+\sin\varphi}}{\dfrac{2c\cos\varphi}{1+\sin\varphi}} \right)^{\frac{1}{2}} \tag{12}$$

Obviously, K images the increasing extent of roof collapsing span after bolted, so it is named after the potential coefficient for reinforcing roof.

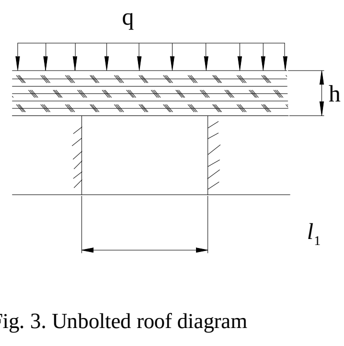

Fig. 3. Unbolted roof diagram

3. Roof reinforcing design procedure and applications

3.1 Design procedure

(a) Aiming at the in-situ geological condition and stress distribution, potential coefficient *K* for roof reinforcing is calculated.

(b) With the calculated *K* and anchor length or bolted roof thickness *h*, the limit tensile strength of bolted roof is calculated by

$$[\sigma_t]_c = K^2[\sigma_t] \tag{13}$$

(c) The volumetric ratio of anchors *f* is calculated by

$$f = \frac{[\sigma_t]_c - \dfrac{2c'\cos\varphi}{1+\sin\varphi}}{\sigma_b - \dfrac{2c'\cos\varphi}{1+\sin\varphi}} \tag{14}$$

(d) The density *n* of anchor is calculated by

$$n = \frac{4f}{\pi d^2} \tag{15}$$

where *d* is the diameter of anchor.

3.2. Applications

Example 1: Roadway No. 4304 in Xinlongzhuang Mine was supported by anchors. With the help of in-situ practice, the anchor reinforcing potential is made. The dip angle of coal seam is 0~15°, buried depth is 282 m, the width and height of the roadway are 4.0 m and 2.8 m. The direct roof of the roadway is a layer of coal seam being 1.6m in thickness. The mechanical properties of coal seam are: 2.4 MPa in cohesion, 1.1 MPa in tensile strength and 30° in interior friction angle. The reinforcing parameters are listed in table 1.

Table 1. Anchor reinforcing parameters

	Length (m)	Diameter (mm)	Space (m×m)	Bolting force (KN)	Count
Roof	2.5	20	0.7×0.8	68.6	6
Wall	2.5	20	0.7×0.8	58.8	4

By sound wave detection, the strength reduction factor ζ of coal seam can be easily obtained. So the coal roof strength after bearing multi-mining affection is $[\sigma_t]_c' = \zeta[\sigma_t]_c$. Through calculation, it is found that the anchor reinforcing potential coefficient without bearing mining affection is K=2.14; the anchor reinforcing potential coefficient bearing the first mining affection is K=1.58.

Example 2: The roadway No. 2307 buried 410 m underground in Baodian Mine is 4m wide and 2 m high, and the roof is a layer of 1.8m thick coal seam whose cohesion is 2.6 Mpa, tensile strength is 0.9 Mpa, and interior friction angle is 32°. The anchor length is 2.0 m, diameter is 20 mm. The anchor reinforcing potential coefficient is selected as K=2.0. Through calculation, the density of anchor for reinforcing roof is 1.73 sets/m^2. Practice showed the roadway is minor in deformation, so the reinforcing parameters are reliable.

5. Conclusions

(1) Based on the brittle damage mechanics and composite mechanics, the collapsing span l_1 without bolted and the collapsing span l_2 with bolted of roof in a roadway is deduced, and the new concept of anchor bolting potential coefficient is defined by $K=l_2/l_1$, which is valuable for evaluating the safety of bolted roadway in coal mine.

(2) With the help of anchor bolting potential coefficient a new anchor reinforcement design method is proposed. It is showed by in-situ testing that the method is reliable.

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